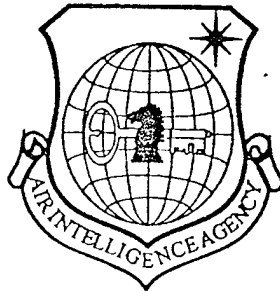# NATIONAL AIR INTELLIGENCE CENTER

COMPOUND CAVITY OF PULSED DYE LASER TUNED
BY USING GLANCING-INCIDENCE GRATING

by

Lu Tongxing, Zhao Xianzhang, He Guanglong

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COMPOUND CAVITY OF PULSED DYE LASER TUNED
BY USING GLANCING-INCIDENCE GRATING

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Abstract. The operating properties of a compound-cavity
pulsed dye laser, which is tuned by means of glancing-incidence
grating, is analyzed theoretically in this paper.  We found the
conditions under which the compound cavity can narrow the laser
linewidth and increase laser energy.  The experimental
results are consistent with theory.

Key words: compound cavity, dye laser.

In many research fields using a laser as the light source,
such as research on high-resolution power light spectra, it is
required that the laser be continuously tuned, but also very
narrow laser linewidth is required.  Therefore, how the linewidth
can be narrowed is always one of the important topics in laser
technology.  Shoshan et al. [1, 3] applied the beam expansion
method of the glancing-incidence grating to realize the purpose
of narrowing the linewidth.  The article studies a method of

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applying a compound cavity in a dye laser with a glancing-incidence gravity to further narrow the laser linewidth and to increase the laser output energy. The improvement of the output properties of a compound-cavity laser was first proposed by Bjorkholm [4]. Then he placed a semireflecting mirror in front of a tuning grating of a dye laser, which was tuned with the grating, in order to prevent intense light from damaging the grating by burning. Unexpectedly, it was discovered in the experiment that this setup not only can protect a grating from being damaged by intense light, but also can better narrow laser linewidth and increase the output energy. At present, compound cavities have been extensively applied in the branch selection technique of $CO_2$ lasers [5, 6]. However, there are few research papers on the application and theoretical analysis of dye lasers.

Theoretical Analysis of Compound Cavity

    1. Effective reflective index $R_c$ of compound cavity

    Fig. 1 is a schematic diagram of the experimental setup. In the figure, G is the grating; $M_1$ is a completely reflective mirror; $M_2$ is a tuning reflective mirror; and $M_3$ is a semi-transparent lens. A beam from the $N_2$ laser passes through the cylindrical-surface lens to focus on the dye pump. Upon exiting from the dye pool, the light is at glancing incidence to the grating at an incidence angle approaching $90^\circ$. If the appropriate grating constant is selected, after diffraction following passage through grating G, two light beams (level 1 and

level 0) will be divided.  If there is no $M_3$, level 1 light
oscillates in the main resonant cavity $M_1$-G-$M_2$; level 2 is the
output light from the laser.  If a semi-transparent lens $M_3$ is
placed, then some of the level 0 light, upon reflection from $M_3$,
will produce sub-zero level and sub-one level light generated
upon diffraction from grating G.  Sub-level light will be lost,
and only sub-zero level light returns to the resonant cavity.
Thus, a supplementary cavity is formed, consisting of $M_1$-G-$M_3$,
with mutual interference occurring with light from the main
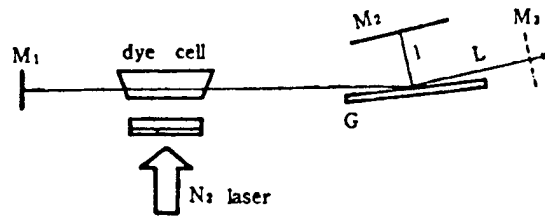resonant cavity.



Fig. 1. Optical path diagram of compound-cavity
dye laser tuned with glancing-incidence grating

Assume that the light beam exiting from the dye pool can be
expressed as $A\exp(i\cdot phi_0)$; A is the oscillation amplitude of the
light beam; $phi_0$ is its phase angle.  Then, the level 1 light
beam and the level 0 light beam generated from the grating
diffraction are, respectively:

$$A\sqrt{Rg_1}\ \exp[i(\phi_0 + 2\pi s/\lambda)]$$

$$A\sqrt{Rg_0}\ \exp[i(\phi_0 + 2\pi s/\lambda)]$$

In the equations, $Rg_1$ and $Rg_0$ are, respectively, level 1 and
level 0 reflective indexes of the grating.  After reflection from

$M_2$ and again diffraction with D, the level 1 light beam enters
into the resonant cavity as

$$A\sqrt{Rg_1} \cdot \sqrt{Rg_1} \cdot expi[\phi_0 + 2\pi(2s+2l)/\lambda]$$

The sub-zero level wave returned from reflection by $M_3$ is

$$A\sqrt{Rg_0} \cdot \sqrt{R_3} \cdot \sqrt{Rg_0} \cdot expi\left[\phi_0 + \frac{2\pi}{\lambda}(2S+2L)\right]$$

In the equation, $R_3$ is the reflective index of $M_3$. Thus, the
overall light beam returning to the resonant cavity is

$$A\sqrt{R_c}\, e^{i\phi'} = Aexpi\left[\phi_0 + \frac{2\pi}{\lambda}(2S+2l)\right] \cdot (Rg_1 + Rg_0\sqrt{R_3}\, e^{i2\Delta\phi}) \tag{1}$$

In the equation, $R_0$ is called the effective reflection index of
the compound cavity

$$\Delta\phi = \frac{2\pi}{\lambda}(L-l).$$

From Eq. (1), $R_c$ is derived as:

$$\tag{2}$$

$$R_c = Rg_1^2 + Rg_0^2 R_3 + 2\,Rg_1\sqrt{R_3}\,Rg_0\cos 2\Delta\phi$$

For sake of comparison, the authors analyzed the reflective
index $R_s$ of the simple grating cavity in the absence of $M_3$.
According to general grating formulas, we obtain the grating
level 1 reflective index $Rg_1$ (when lambda = $\lambda_0 + \Delta\lambda$):

$$\tag{3}$$

$$Rg_1 = Rg_{10}\, sinc^2\left(\pi N\frac{\Delta\lambda}{\lambda_0}\right)$$

In the equation, $Rg_{10}$ is the level 1 reflective index of the
grating when lambda = lambda$_0$; N is the number of fringes at the
grating with light beam illumination. Therefore, $R_s$ can be
expressed as:

$$R_s = Rg_1^2 = Rg_{10}^2\, sinc^4\left(\pi N\frac{\Delta\lambda}{\lambda_0}\right) \tag{4}$$

Substitute Eq. (3) into Eq. (2) and we obtain that the effective
reflective index $R_0$ of the compound cavity is:

$$R_c = Rg_{10}^2 sinc^4\left(\pi N\frac{\Delta\lambda}{\lambda_0}\right) + Rg_0^2 R_3$$
$$+ 2Rg_0 Rg_{10}\sqrt{R_3}\ sinc^2\left(\pi N\frac{\Delta\lambda}{\lambda_0}\right)\cos\left[\frac{2\pi}{\lambda_0 + \Delta\lambda}\cdot 2(L-1)\right] \tag{5}$$

As discovered from calculating Eq. (5), the maximum value of
$R_0$ may change several times at lambda=lambda$_0$ with change of
DELTA l=L-1. When $Rg_{10}$=0.8, $Rg_0$=0.15, $R_3$=0.7, N=34,000 (here
d=1200/mm and alpha=4$^0$), Fig. 2 shows the curve $R_0$ proportional
to DELTA lambda at three positions of DELTA l: 1.00002, 1.50000,
and 2.70000cm. In the figure, the curve of the effective
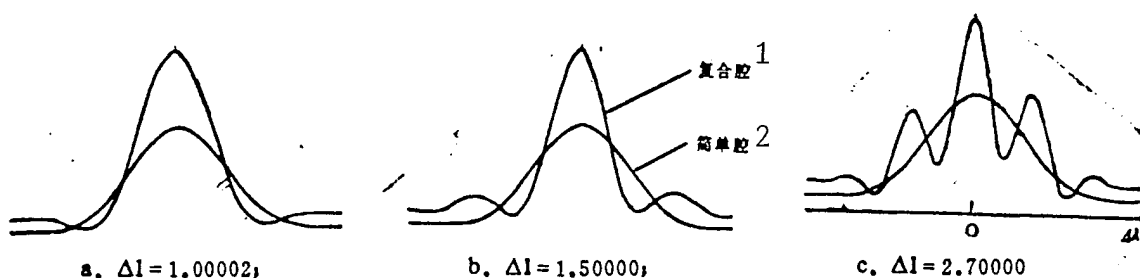reflective index $R_s$ of the simple grating cavity is also drawn.



a. $\Delta l = 1.00002$,     b. $\Delta l = 1.50000$,     c. $\Delta l = 2.70000$

Fig. 2. Curves $R_0$ proportional to DELTA lambda
for several DELTA l values, in the case alpha=4$^0$
KEY: 1 - compound cavity  2 - simple cavity

From the figure, the maximum positions of $R_c$ and $R_s$ are
coincident at lambda=lambda$_0$. Of interest is the fact that, with
an increase in DELTA l, $R_c$ has a multiple-peak structure. For
example, at DELTA l=1.00002cm, there is one distinct main peak
for $R_c$. However, at DELTA l=2.70000cm, except for the central
main peak, in its left and right there are symmetrically
distributed two small peaks with amplitude gradually decreasing.

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Besides, with increase in DELTA 1, the main peak becomes narrower and narrower. When DELTA 1 changes minutely near the position of maximum value, the $R_c$ curve will have changed sensitively as shown in Fig. 3. In other words, the peak value position of $R_c$ has shifted; the wave peaks are not symmetric and the height of the peak value has decreased.
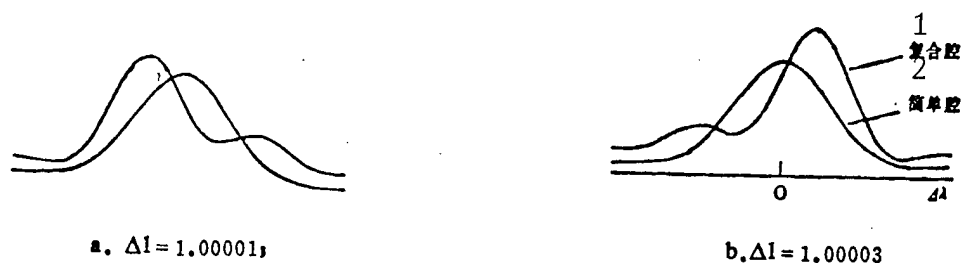


a. $\Delta l = 1.00001$,                                b. $\Delta l = 1.00003$

Fig 3. Effect on symmetry of curve $R_c$ wave DELTA lambda of minute changes in DELTA lambda, in the case alpha=4°
KEY: 1 - compound cavity 2 - simple cavity

Fig. 4 is the curve showing the relationship between $R_c$ and DELTA-1 when alpha=4.8°. By comparing Figs. 4 and 2(b), we can see that the wave peaks $R_c$ are more numerous and that the main peak is narrower at the same DELTA 1 with larger glancing angle.
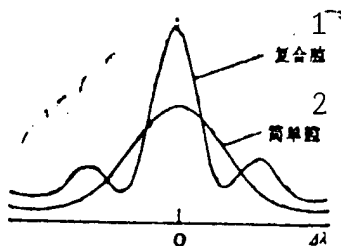


Fig. 4. Effect on curves $R_c$ proportional to DELTA lambda for changes in glancing angle alpha: in the figure, alpha=4.8° and DELTA 1=1.5000
KEY: 1 - compound cavity  2 - simple cavity

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## 2. Output power

The following relationship holds between laser output and cavity reflective index:

$$P = AI_0 = \frac{1}{2} I_s A (1 - a_h - R) \left( \frac{g_0}{a_s - \frac{1}{2 L'} \ln R} - 1 \right)$$

(6)

In the equation, $I_0$ is the output light intensity; $I_s$ is the saturated light intensity; A is the average laser beam cross-sectional area; $a_h$ is the lens surface wear at the output terminal of the cavity; R is the effective reflective index; $g_0$ is the gain coefficient of lambda$_0$; $a_0$ is wear in the cavity; and L' is the length of the dye pool. Substitute Eqs. (4) and (5) in Eq. (6) and then we obtain that the output power of the simple cavity and the output of the compound cavity are as follows:

$$P_s = \frac{1}{2} I_s A (1 - a_{hs} - R_s) \left( \frac{g_0}{a_s - \frac{1}{2 L'} \ln R_s} - 1 \right)$$

(7)

$$P_c = \frac{1}{2} I_s A (1 - a_{hc} - R_c) \left( \frac{g_0}{a_s - \frac{1}{2 L'} \ln R_c} - 1 \right)$$

(8)

If $Rg_{10} = 0.80$, $Rg_0 = 0.15$, $\Delta l = 1.50000$ cm, $N = 34000$, $g_0|_{\lambda_0} = 0.2$, $\lambda_0 = 600$ nm, $a_{hs} = 0.05$, $a_{hc} = 0.1$, $L' = 3$ cm, and $a_0$ at 0.05, 0.10, and 0.15, respectively, then the relationship curves can be plotted between 2 Ps/IsA and 2 Pc/IsA and the wavelength, from the two equations (7) and (8). Fig. 5 shows the relationship curves. We can see that the semi-height width $\delta \lambda_c = 0.042 \frac{\lambda_0}{N}$ nm, of the power distribution curve for the simple cavity. The semi-height width

$\delta\lambda s = 0.066 - \dfrac{\lambda_0}{N}$ nm, for the power distribution of the compound

cavity. The ratio between the two peak widths is $\delta\lambda_c/\delta\lambda_s = 0.64$, ;

$P_c/P_s = 2$ is the ratio of two peak values. In other words, in

conditions that the authors assumed, the compound cavity has

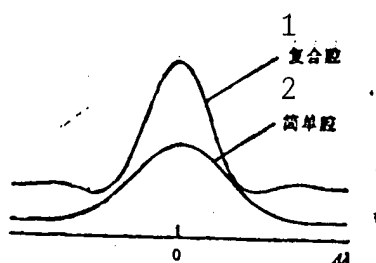narrower output linewidth and higher output power than that of

the simple cavity.



Fig. 5. Output power curves of laser for compound cavity
and simple cavity
KEY: 1 - compound cavity   2 - simple cavity

Experimental Results

The dye used in the experiments was rhodamine 6G, and the

alcohol concentration was at the concentration $1.5 \times 10_{-3} mol/m^3$. By

using the $N_2$ laser as the pumping source, the pulse energy was

2mJ. The length of the dye pool was 3cm; and the grating

constant d=1200/mm. As shown in Fig. 1, L=4cm and l=3cm; the

reflective index (of the semi-transparent lens $M_3$) $R_3 = 0.70$.

Other element parameters are shown as above.

Measurement of linewidth for the dye laser employed the

Fabry-Perot interferometer. The Fabry-Perot spacing d=5mm; for

the free light spectral zone, the spacing was 0.036mm

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(lambda$_0$=600nm). The mirror reflective index R=0.90; and the precision constant was approximately 60. A model RJP-700 energy meter was used to measure the pulse energy of the dye laser.

In the situation where the glancing angle alpha=$4^0$, measurements were conducted on changes in linewidth in the absence of the compound cavity: $\delta\lambda_s = 0.024\,\text{nm}, \delta\lambda_c = 0.016$ nm, $\delta\lambda_c/\delta\lambda_s = 0.67$.

This value is very close to $\delta\lambda_c/\delta\lambda_s = 0.64$ , as calculated theoretically.

When the grazing angle alpha=$4^0$, the measurements were made of the laser pulse energy before and after the absence of M$_j$, P$_s$=1.5, P$_c$=2.2, and P$_c$/P$_s$=1.5. These values are also very close to the theoretical value P$_c$/P$_s$=2. From the theoretical and experimental data, with the semi-reflective mirror M$_j$ for the compound cavity, not only does the laser linewidth become appreciably narrower, but also the output energy becomes obviously higher.


Discussion

As proven from the authors' theoretical analysis and experimental results, by placing the semi-reflecting mirror M$_j$, the purpose of narrowing the laser linewidth and increasing the output energy can be really attained. In the situation when the glancing angle is $4^0$, the laser linewidth is narrowed to half its previous value, but the output energy is increased by 50%. However, the following points should be noted with respect to the optical path:

(1) From the discussion of the relationship between DELTA 1 and the curve $R_c$ proportional to DELTA lambda, we know that the curve has a multiple-peak structure with increase in DELTA 1, but the central main peak is also steeper. There is a similar pattern between the output energy distribution and the curve $R_c$ proportional to DELTA lambda. Hence, in order to obtain a narrower laser linewidth, a greater value of DELTA 1 is preferably selected within the allowable situation of laser dimensions.

(2) Since a slight change in DELTA 1 will deteriorate the symmetry of the curve $R_c$ proportional to DELTA lambda with increase in the main peak width, increasing the output linewidth, [.... to be continued on text page 160, not supplied-- Translator].

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